Towards an Integrated Environment for Modeling and Simulating an Electro-Optical Measurement Microsystem

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ABSTRACT: The problem of tools for modeling simulating and testing measurement microsystems is addressed. The design methodology underlying the proposed integrated software & hardware environment for modeling and simulating measurement microsystems is based on functional simulation of the whole system and on step-by-step replacement of the simulated blocks of the designed system by real ones. The environment allows for modeling, simulating, and testing different combinations of the optical transducers and dedicated electrical processors in order to arrive at overall optimization of the measurement microsystem under development: an integrated spectrometric sensor in our case. Examples of application of the environment for optimization of efficiency of the digital signal processing in the integrated spectrometric sensor under development are shown.

Keywords: integrated design environment, modeling, simulation, measurement microsystems, spectrometric sensor.

1. INTRODUCTION

Recent developments of measuring systems enhanced by the achievements of digital signal processing, microelectronics, micromachining and microoptics, have made it possible to improve the quality of measurements by means of direct association of microsensors with dedicated processor performing sophisticated algorithms of signal processing implemented using VLSI technology. An enormous amount of catalog-type knowledge about sensors, transducers, converters, interfaces, processors, etc., and also - unusual diversity of design strategies and procedures, evaluation criteria and techniques of analysis are available for the designers. Modern CAD tools should be used to carry out the successful design of a microsystem.

In this situation, a purely additive (accumulative) approach to dealing with this stream of information is unthinkable, neither in relevant teaching practice nor in design practice. This is the main incentive for developing "unified approaches" to measurement problems [1]-[4] which, by means of abstraction, enables one to grasp the diversity of knowledge using a relatively limited system of concepts and rules. The system approach seems to be a natural conceptual basis for the functional and technological integration of measuring systems. Development of the design methodologies and corresponding flexible design environments for modeling and simulating measurement microsystems, including the necessary software and hardware blocks, is of basic importance.

The Sections which follow will include: a summary of the unified conceptual basis for the design and development of the measurement microsystems (Section 2); a short presentation of the electro-optical measurement microsystem: an intelligent integrated spectrometric sensor/transducer (IISS/T), (Section 3); a functional specification of the proposed environment (Section 4) ; examples of application of the developed environment for the optimization of the efficiency of the digital signal processing in the IISS/T under development (Section 5), and finally the perspectives on the future development of the environment for other applications.

2. SUMMARY OF THE UNIFIED CONCEPTUAL BASIS FOR THE DESIGN AND DEVELOPMENT OF MEASUREMENT MICROSYSTEMS

System approach to electrical measurements

The system approach to electrical measurements [1] constitutes an example of a unified vision of measurement and its instrumentation, and provides a unified conceptual basis for the modern interdisciplinary development of measuring systems. The general model of the measuring system according to this approach is shown in Fig.1.

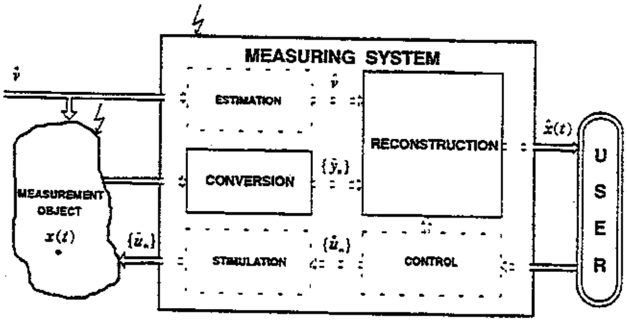

Fig. 1. General measurement specific model of measuring system

In this figure: x is a vector of scalar variables modeling physical quantities (such as voltage, light intensity, temperature, etc.), and t is a vector of scalar variables modeling other physical quantities (e.g. time, length, temperature); $x(t)$ denotes the measurand, $\{y_n\}$ - the raw result of measurement, $\hat{x}(t)$ - denotes the final measurement result, v - the vector of influence quantities, $\{u_n\}$ - the signal stimulating the measurement object.

The process of measurement may be now described as follows. The object of measurement, stimulated with the signal $\{\tilde{u}_n\}$, responds with the signals that are converted by sensors, transducers, conditioning circuits and analog-to-digital converters into the raw result of measurement $\{\tilde{y}_n\}$. The final result of measurement is determined on the basis of the raw result of measurement $\{\tilde{y}_n\}$, using the estimated (measured) value of the vector of influence quantities $\hat{v}$ and the exact value of the stimulating signal $\{\dot{u}_n\}$:

$$\hat{x}(t)=\mathrm{R}\left[\{\tilde{y}_n\};\ \hat{v},\ \{\dot{u}_n\}\right].$$

As shown in [2], all the measurement-specific functions of the measuring system, indicated in Fig. 1, may be accomplished by appropriate processing of measurement signals. In Fig. 2, a corresponding model of a measuring system has been presented, where A denotes analog signals, D - digital signals, and / - their conversion. According to this model, the main function of any measuring system may be decomposed into four kinds of signal conversion:

- analog-to-analog conversion (as performed by sensors, transducers and conditioning circuits);
- analog-to-digital conversion (as performed by voltage-to-code or time-to-code converters);
- digital-to-digital conversion (as performed by computers or digital signal processors);
- digital-to-analog conversion (as performed by code-to-voltage or code-to-time converters).

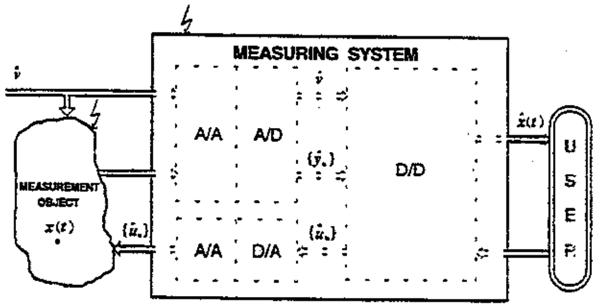

Fig. 2. General measurement non-specific model of measuring system

Since the design of a measuring system is a special case of the general "top-down" design process which can be supported by CAD tools, the system approach to electrical measurement becomes a particularly useful basis for working out an effective design methodology and environment [2].

Process of designing a measuring system

The process of designing a measuring system is relatively complex, since it involves [5]-[7]:

- hardware and software design,
- analog, digital and mixed design,
- numerical and symbolic processing of information,
- algorithmic and heuristic elements,

The general design scheme is presented in Fig. 3.

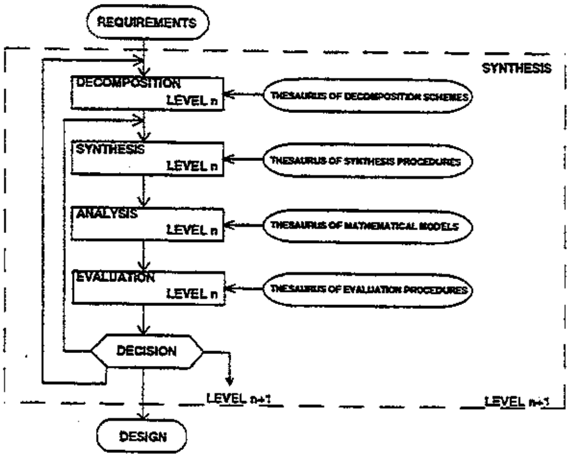

Fig. 3. General design scheme

In this Figure :

- REQUIREMENTS allows the formalization of various informal, incomplete (often contradictory) requirements and expectations of the potential users of a designed measuring system;
- DECOMPOSITION allows the generation of the criteria of decomposition and apply them consistently for restructurization of the requirements;
- SYNTHESIS allows the use of existing algorithms and/or acquire new algorithms of synthesis at the highest applicable level (the greatest value of n) of synthesis;
- ANALYSIS allows the choice of proper mathematical models and adequate means of simulation for the analysis of partial or final results of design;
- EVALUATION allows the transformation of formal and/or informal requirements for a designed measuring system into the criteria of evaluation for the results of design);
- DECISION allows the deduction of conclusions from the results of evaluation and to undertake reasonable design decisions.

3. ELECTRO-OPTICAL MEASUREMENT MICROSYSTEM UNDER DEVELOPMENT

The measuring microsystem under development is an intelligent integrated spectrometric sensor/transducer (IISS/T) [8]-[11]. A method for providing an IISS/T is proposed in order to fill the gap existing between the excellent tools for spectrum measurements in the laboratory environment and very poor (practically non-existent) tools for spectrum measurements available for in situ applications. To do this, it is of basic importance to provide an IISS/T using standard integration technologies in order to make it possible to manufacture spectrum-measurement-based portable and easy-to-use instruments, at significantly reduced costs when compared to the prices of available spectrometers.

The proposed new method consists of designing a simple optical device, a signal discretization block and a specialized digital signal processor and then to combine them in one functionally fused entity: IISS/T as schematically shown in Fig. 4.

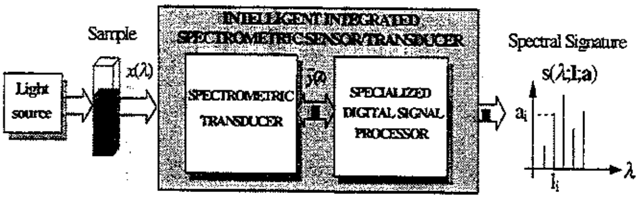

Fig. 4. Measurement principle underlying the intelligent, integrated spectrometric sensor/transducer

In this figure: Sample - is a sample of the substance to be analyzed, $x(\lambda)$ is the spectrum to be measured, $\tilde{y}(\lambda)$ is the raw result of measurement, i.e. the low-accuracy representation of the spectrum $x(\lambda)$, $S(\lambda,l,a)$ is the final result of measurement, the set of characteristic peaks, positions and magnitudes, the so-called spectral signature of the sample under study.

In order to circumvent difficulties with the integration of the optical functions using the semiconductor-based integration technologies, the basic idea of the proposed method for providing a IISS/T, is based on transferring the problem of the accuracy of measurement from the domain of optical analog signal processing to the domain of electrical digital signal processing (much easier to integrate).

An envisaged example of the sensor's generic structure is shown in Fig. 5.

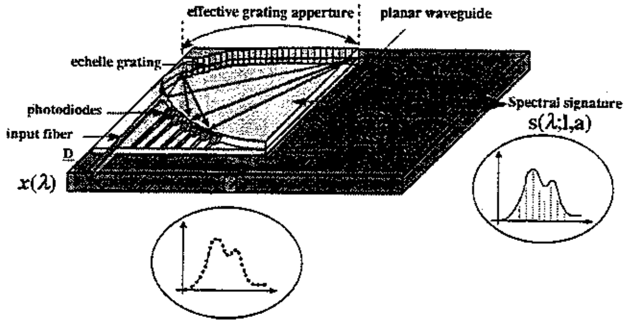

Fig. 5. Envisaged example of a generic structure of the intelligent, integrated spectrometric sensor

4. FUNCTIONAL SPECIFICATION OF THE PROPOSED INTEGRATED (HARDWARE & SOFTWARE) ENVIRONMENT

The design methodology underlying the proposed integrated software & hardware environment for modeling and simulating measurement microsystems is based on functional simulation of the whole system and on step-by-step replacement of the blocks of the designed system by real ones.

Referring to the models of measuring systems and to the design methodology described in Section 2, one may conceptualize an integrated software & hardware environment for modeling and simulation of measurement microsystems. Its structure is presented in Fig. 6. and Fig. 7.

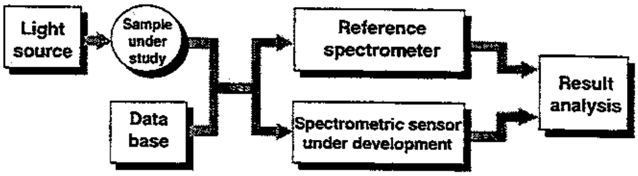

Fig. 6. General structure of the proposed environment

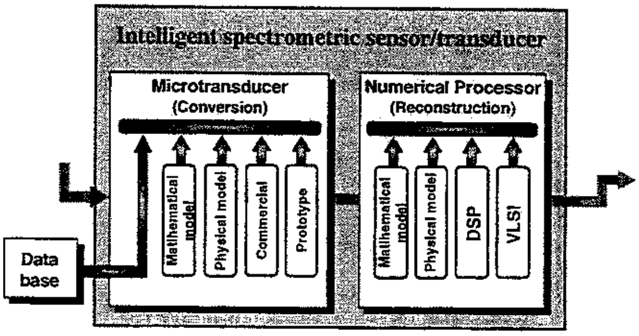

Fig. 7. Focus on the IISS/T under development in the proposed environment

The environment allows for modeling, simulating, and testing different combinations of the optical transducers and dedicated electrical processors as shown in Fig.7. It means that in this environment, both parts of the integrated spectrometric sensor, optical and electrical, can be simulated and tested at different stages of their development and compared with the reference instrumentation or data.

In particular:

- a mathematical model of the spectrometric microtransducer and of the digital signal processor was developed and tested with real-world data. The functional model of the complete electrooptical microsystem is operational using MATLAB software;
- a hybrid laboratory model of the spectrometric sensor can also use the optical processor of the commercially available microspectrometer, Ocean Optics S1000, and the commercially available DSP, both interfaced to be a part of the environment;
- models of transducer and of the processor taking into account the technological parameters are under development using VHDL, HDL-A languages and Mentor Graphics software.

The correspondence between the internal structure of the environment and the users is shown in Fig. 8.

5. EXAMPLES OF APPLICATION OF THE INTEGRATED ENVIRONMENT

The developed environment is currently used to arrive at overall optimization of the efficiency of the signal processing in the integrated spectrometric sensor under development.

To do so, one of basic experiments is repeated iteratively. It simulates the case of a low-cost, low-resolution (for example 15 nm) spectrometric microtransducer, the metrological imperfections of which are enhanced by the specialized electrical processor with a set of algorithms using information about imperfections of the spectrometric microtransducer acquired during the calibration process.

An example of the results of the simulation is shown in Fig. 9. The global black-box parameters of the integrated sensor correspond to the result obtained from a commercial spectrometer with resolution exceeding 1 nm.

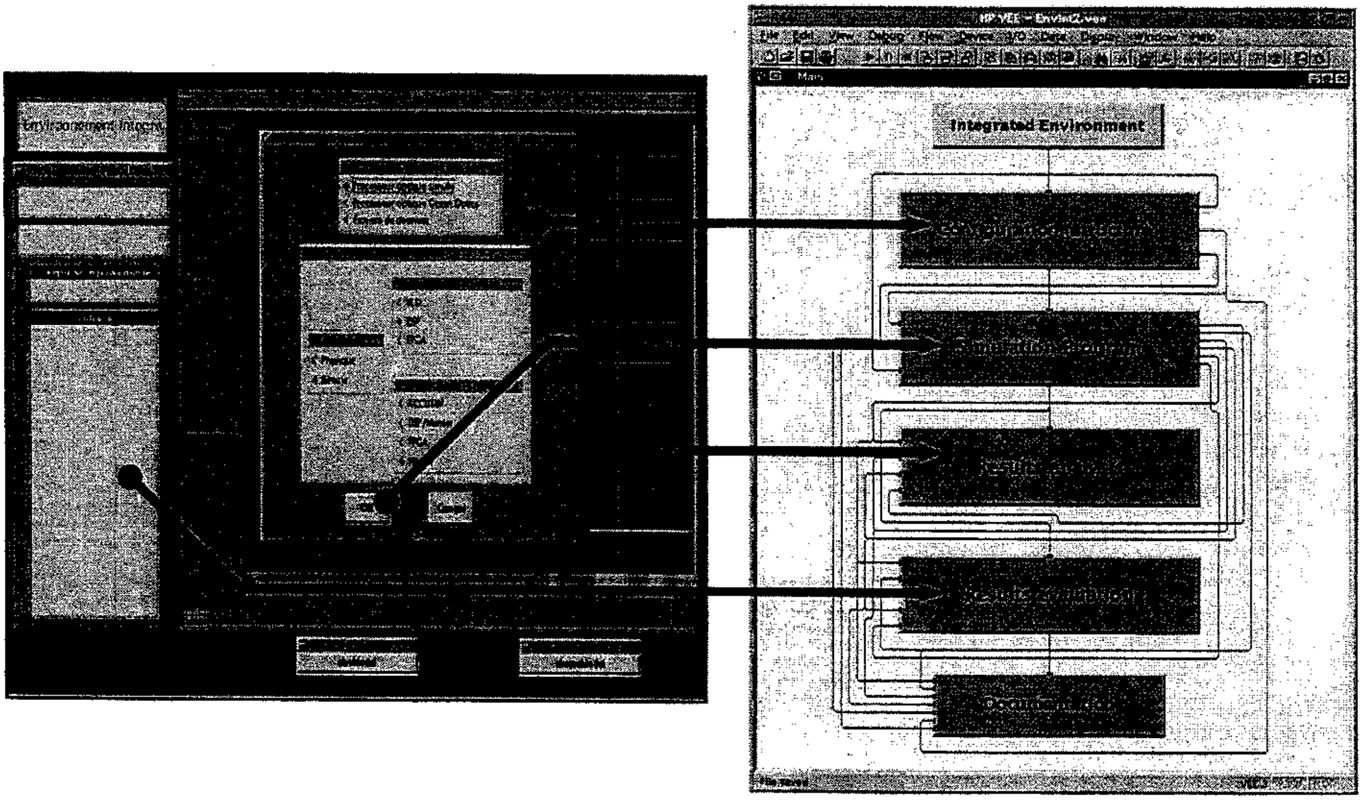

Fig. 8. The correspondence between the internal structure of the environment and the user interface

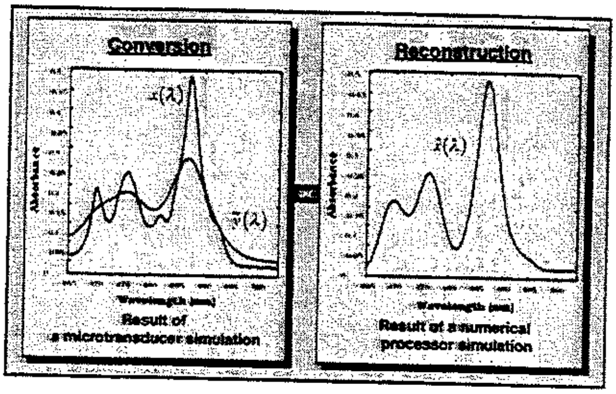

Fig. 9. Efficiency of the developed signal processing algorithms of correction the imperfections of the optical processor

In this figure:

- $x(\lambda)$ is the reference data, CARY-3 (Varian) 0.2 nm resolution;
- $\tilde{y}(\lambda)$ is the raw result of measurement of 15 nm resolution, simulated using microtransducer mathematical model;
- $\hat{x}(\lambda)$ is the spectrum reconstructed from $\tilde{y}(\lambda)$ using the designed processor.

Another example illustrating the overall efficiency of the signal processing in the spectrometric microtransducer is shown in Fig. 10 where an additional algorithm is used for computing the parameters of the analyzed spectrum, the so-called spectral signature of the analyzed solution.

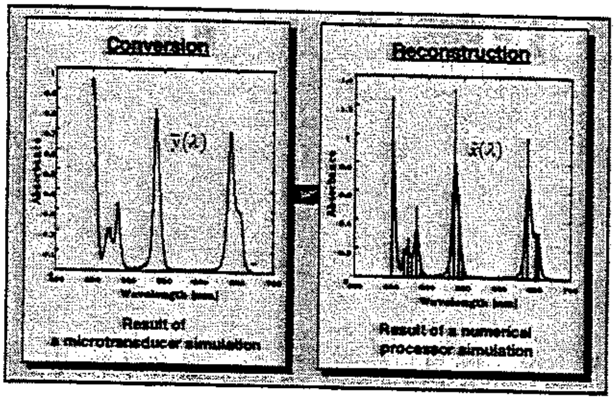

Fig. 10. Results of experiments using the mathematical model of the microspectrometer

In this figure:

- $\tilde{y}(\lambda)$ is the raw result of measurement of 5 nm resolution, simulated using microtransducer mathematical model;
- $\hat{x}(\lambda)$ is the spectrum reconstructed from $\tilde{y}(\lambda)$ using the mathematical model of the processor.

In this experiment, the spectrum of the standard Holmium perchlorate test solution, of 5 nm resolution was simulated using the mathematical model of the spectrometric microtransducer realized in MATLAB. Then the lower-quality result was processed by the model of the numerical processor in order to arrive at the higher-quality results.

6. CONCLUDING REMARKS

The developed environment for modeling and simulation of measurement microsystems is one of the basic elements helping the R&D program, concerning the development of an integrated spectrometric sensor/transducer, to make progress.

The future works will consist of :

- completing the software modeling of the behavioral level of the sensor,
- enhancing the environment with the developed microsystem's test equipment which will be interfaced to the environment throughout the VXI and/or IEEE-488 buses, like other hardware functional blocks of the environment,

and will permit more flexibility in the development of other measurement microsystems.

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